

# A Variety of Decays of Gamma-Ray Burst Pulses

Felix Ryde<sup>1,2</sup> and Roland Svensson<sup>2</sup>

<sup>1</sup> Center for Space Science and Astrophysics, Stanford University, Stanford CA 34305

<sup>2</sup> Stockholm Observatory, SE-133 36 Saltsjöbaden, Sweden

## Introduction

The main target of this study is the GRB light curve during the decay phase of long, bright pulses. As shown by Ryde & Svensson (2000; hereafter RS00) approximately half of these decays can be described by a power law  $\propto 1/(\text{time})$ . This happens for cases when the hardness-fluence correlation (HFC) is an exponential function,  $E_{\text{pk}}(\Phi) \propto e^{-\Phi/\Phi_0}$ , and the hardness-intensity correlation (HIC) is a power law,  $E_{\text{pk}}(N) \propto (N/N_0)^\delta$ . Here,  $N(t)$  is the instantaneous photon flux,  $E_{\text{pk}}(t)$  is the corresponding photon energy, at which the  $E^2 N_{\text{E}}$ -spectrum peaks and is used as a measure of the spectral hardness, and the photon fluence is defined by  $\Phi(t) = \int^t N(t') dt'$ . These most commonly assumed correlations were found by Liang & Kargatis (1996; HFC) and Golenetskii et al. (1983; HIC).

There obviously exists a large group of GRB pulses which decay in a different way. In this paper, we search for alternative descriptions of the spectral/temporal evolution. We use the complete sample of long pulses in strong bursts presented in Ryde & Svensson (2001) consisting of 25 pulses within 23 bursts observed by BATSE on the *CGRO* during its entire mission (1991 – 2000). The spectral analysis of the LAD/HERB data ( $\sim 25 - 1900$  keV) was performed with the WINGSPAN/MFIT package (Preece et al. 1996). For each time bin the photon spectrum with the background subtracted was determined using the Band et al. (1993) function with both its power law indices left free to vary. The instantaneous, integrated photon flux,  $N(t)$ , was found by integrating the modeled photon spectrum over the available energy band.

## Other Types of Behaviors

There is no consensus on what shape the pulse decays have. Both power law and stretched exponential decays have been used. Guided by the findings of RS00 we study the following generalized power law decay:

$$N(t) = \frac{N_0}{(1 + t/\tau)^n}, \quad (1)$$

where  $t$  is taken from the start of the decay, when  $[N(t), E_{\text{pk}}(t)] = [N_0, E_{\text{pk},0}]$  and the time constant  $\tau \equiv \delta\Phi_0/N_0$ , where  $\Phi_0$  is the exponential decay constant

of the exponential HFC and  $\delta$  is the index of the power law HIC. The photon fluence associated with equation (1) when  $n$  differs from 1 becomes

$$\Phi(t) = \frac{N_0\tau}{n-1} \left\{ 1 - (1 + t/\tau)^{-(n-1)} \right\}, \quad n \neq 1, \quad (2)$$

which for  $n$  larger than 1, converges to the asymptotic value  $f_0 \equiv N_0\tau/(n-1)$ .

Now, we consider two different alternatives. First, for GRB pulse light curves whose decays follow equation (1), and for which the HFC  $E_{\text{pk}}(\Phi)$  is an exponential, the HIC  $E_{\text{pk}}(N)$  will follow

$$E_{\text{pk}}(N) = E_{\text{pk},0} \exp \left\{ \frac{f_0}{\Phi_0} \left[ \left( \frac{N}{N_0} \right)^{(n-1)/n} - 1 \right] \right\}, \quad n \neq 1. \quad (3)$$

When  $\ln(N_0/N) \ll 2n/|n-1|$  the HIC approaches a power law with the exponent  $\delta/n$ , which becomes identical to the original power law HIC, when  $n$  tends to 1. On the other hand, if the HIC  $E_{\text{pk}}(N)$  actually is a power law then the HFC  $E_{\text{pk}}(\Phi)$  will follow

$$E_{\text{pk}}(\Phi) = E_{\text{pk},0} \left( 1 - \frac{\Phi}{f_0} \right)^{n\delta/(n-1)}, \quad n \neq 1, \quad (4)$$

which behaves similarly to the exponential HFC as  $n$  tends to 1.

We also fitted the decays with a stretched exponential:  $N \propto \exp(-(t/\tau_d)^\nu)$ , where  $\tau_d$  is the time constant for the decay phase and  $\nu$  is the peakedness parameter. This function is the most commonly assumed pulse shape used so far (e.g. Norris et al. 1996).

Our study showed that, first, a power law gives a better description of the pulse decays than a stretched exponential and, second, the power law index (Eq. 1) has a bimodal distribution in that there are two preferred values  $n = 1$  and  $n \sim 3$  (See Fig.1). The sample is divided into approximately two equally large sets by  $n \sim 2$ . For the 11 pulse decays with  $n$  larger than 2, we found that for each case either the HIC  $E_{\text{pk}}(N)$  or the HFC  $E_{\text{pk}}(\Phi)$  is still valid, while the other corresponding correlation is different, and thus described by a new function. To be able to get constrained fits on all cases we had to freeze the values of  $N_0$  and  $n$  to the values obtained from the fits of the light curve.

Six out of these eleven cases are, however, good enough for  $n$  to be constrained. Four out of these gave  $n$ -values that were the same to within the errors as the values obtained from fitting the light curve. In the last two cases the errors in the  $n$ -values were so large that no certain conclusion could be drawn. In all of these four cases the power law HIC  $E_{\text{pk}}(N)$  is valid.

This suggests that the important relations for a GRB pulse decay are the power law HIC  $E_{\text{pk}}(N)$  and the light curve,  $N(t)$ . The power law correlation between the hardness and the intensity is valid independent of the shape of the light curve. The HFC  $E_{\text{pk}}(\Phi)$ , on the other hand, is different for different light curve behaviors according to equation (4), since the fluence is the time integral of the instantaneous flux.

In Figure 2 one of these cases, GRB960807, is presented. The first panel shows the DISCSC data (all four energy channels) and indicates the time interval studied and the second panel shows the light curve with the LAD HERB data in the chosen time binning. The best fit is indicated with a solid curve. The two left-hand panels, show the correlations, the HIC  $E_{\text{pk}}(N)$  in panel 3 and the HFC  $E_{\text{pk}}(\Phi)$  in panel 4. The fit of an exponential HFC is shown by a dashed line.

## ACKNOWLEDGMENTS

We are grateful to the GROSSC at NASA/GSFC for providing the HEASARC Online Service. We acknowledge financial support from the Swedish Foundation for International Cooperation in Research and Higher Education (STINT) and the CF Liljevalch J:or Fund at Stockholm University.

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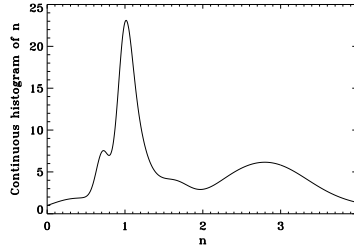


Fig. 1. Continuous histogram of the power law index  $n$ .

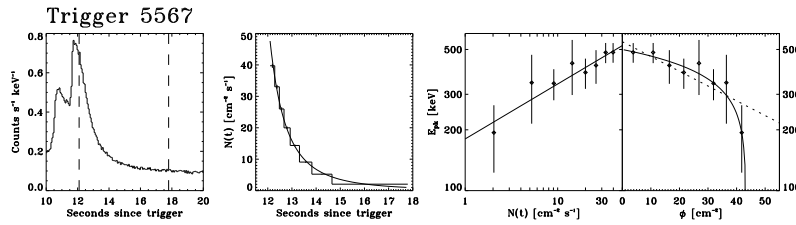


Fig. 2. Spectral and temporal behaviour of GRB960807 (BATSE trigger 5567).